STUDY OF COLLIDING-SHELL CONFIGURATIONS TO REDUCE THE EFFECTS OF MAGNETIC RAYLEIGH-TAYLOR ON IMPLODING LINERS

R.J. Faehl, W.L. Atchison, R.K. Keinigs, I.R. Lindemuth, R.E.Reinovsky
Los Alamos National Laboratory, New Mexico, USA

Abstract

We present computational studies on the use of colliding shell configurations to mitigate the effects of Magnetic Rayleigh-Taylor (MRT) on the inner liner. Two-dimensional MHD calculations of liners have been performed that have pre-formed, single wavelength perturbations. Specifying the perturbation allows us to follow the evolution of a specific disturbance with little ambiguity. This technique has been confirmed in numerous experiments on the PEGASUS II machine. An inner liner is located at a smaller radius than the outer, driver liner. The radius is chosen so that the perturbation will grow to large amplitude before impact. To minimize shock effects, a low-density pad is placed between the two liners. This pad may be either plastic or a magnetic field. Results of the computational study will be presented.

I. INTRODUCTION

This study examined the effect of colliding shell interactions on unstable Magnetic Rayleigh-Taylor(MRT) perturbations. The results reported here were obtained primarily from two-dimensional MHD calculations, including strength. Recent experimental data from Russian Federal Nuclear Center (VNIIEF) experiments on the Los Alamos PEGASUS II facility still require analysis, but the preliminary data will be referenced here. In a typical two-shell configuration, single wavelength perturbations were imposed on the outer conducting shell. Amplitudes were chosen to ensure a highly nonlinear level at the time of collision with an inner, unperturbed liner. A certain amount of imprinting was expected during the collision, but it was hoped that this perturbation level would be less than that already on the outer liner. Since the momentum transfer during the collision is impulsive, the surfaces of the inner liner should not be subject to strong acceleration over the rest of its trajectory. Any subsequent growth of perturbations on the inner liner should occur at a reduced growth rate.

Rayleigh-Taylor instabilities in their various manifestations have been exhaustively studied in the last 50 years[1-4]. It might well be supposed that there is nothing new that can be said about this process. (Actually a recent literature search suggests that the rate of new Rayleigh-Taylor papers may be growing exponentially[5].) This study is restricted to unstable growth in materials with strength. Even with this caveat, the literature is extensive[6-13]. It is evident from this literature that strength can modify thresholds, but it does not intrinsically stabilize materials against Rayleigh-Taylor. Miles appears to be the first to recognize that strength leads to stabilization of modes with wavelength shorter than a critical value that depends on the acceleration. Many other treatments also recover this result[8-13]. Drucker was the first to suggest that there was an amplitude threshold for Rayleigh-Taylor instability in materials with strength. Although there is no first principles analysis which exhibits the finite amplitude threshold, this phenomenon has been observed in several experiments[7,13] and has been heuristically modeled by Lebedev, et. al.[13].

The primary results in this paper are obtained by numerical simulation using a two-dimensional (r-z) resistive MHD code[14]. These results are supplemented by simple analytic models and one-dimensional Lagrangian calculations. Preliminary data from experiments performed jointly by LANL and VNIIEF scientists on the Los Alamos pulsed power machine, PEGASUS II, will be compared with calculations.

II. SIMPLE MODELS

There are two aspects to colliding shell interactions. The first is that there must be Rayleigh-Taylor growth of perturbations on the outer liner. The second is that the collision should be as close to elastic as possible. Dissipation of the kinetic energy of the outer liner into internal energy (heating) can have serious consequences, especially if the inner liner is the one which is heated.

Several models have been given for the linear phase of RT growth in strong materials [10-13]. They all begin with the first two moment equations for the material(s), including the Cauchy stress term. Either Prandtl-Reuss or Levi-Mises constraints are imposed to complete the description of strength. These equations are then linearized and the appropriate dispersion relations are extracted. A common feature of these treatments is that they conclude that strength stabilizes sufficiently small wavelengths, and the criterion is, within factors on the order of two,

$$k^*H > (1/2)P_o/G[1 - \exp(-k^*H/3^{1/2})]^{-1} \qquad (1)$$

where k^* is the wavenumber of the shortest unstable wave, H is the plate thickness, P_o is the accelerating pressure, and G is the shear modulus. Lebedev, et. al.[13]

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14. ABSTRACT

We present computational studies on the use of colliding shell configurations to mitigate the effects of Magnetic Rayleigh-Taylor (MRT) on the imter liner. Two-dimensional MHD calculations of liners have been performed that have pre-form& single wavelength perturbations. Specifying the perturbation allows us to follow the evolution of a specific disturbance with little ambiguity. This technique has been confirmed in numerous experiments on the PEGASUS II machine. An inner liner is located at a smaller radius than the outer, driver liner. The radius is chosen so that the perhubation will grow to large amplitude before impact. To minimize shock effects, a low-density pad is placed between the two liners. This pad may be either plastic or a magnetic field. Results of the computational study will be presented.

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derived Eq(1) from equations which model the instability in the thin plate approximation,

$$\partial^2 x/\partial^2 t = 4C^2\, \partial^2 x/\, \partial^2 \xi - g\, \partial y/\, \partial \xi$$
$$\partial^2 y/\, \partial^2 t = -(C^2 H^2/3)\, \partial^4 y/\, \partial^4 \xi + g\, \partial x/\, \partial \xi - g \qquad (2)$$

where $C^2 = G/\rho$. The interesting thing about these model equations, which are not unique, is that they reduce to Ott's nonlinear thin plate theory [4] in the limit that G goes to zero. We have solved this set numerically to gain insight into the nonlinear phase of MRT. These results will be presented in the future.

The kinematic effect of the collision is that the outer liner will lose velocity, while the velocity of the inner liner may be either greater or less than that of the outer liner, depending on the ratio of masses. It is straightforward to show that if the cylindrically imploding outer liner is concentric with the inner one, is not rotating, and has no component of velocity in the axial direction, then a perfectly elastic collision would result in the following velocities after the interaction,

$$V_{out} = V_o\, (M_{out} - M_{in})/(M_{out} + M_{in}) \qquad (3a)$$

and

$$V_{in} = 2M_{out}\, V_o/(M_{out} + M_{in}) \qquad (3b)$$

where V_o is the velocity of the outer liner just before impact, M_{out} is the total mass of the outer liner and M_{in} is the total mass of the inner liner. It is tempting to consider amplifying the velocity of the inner liner by having $M_{in} \ll M_{out}$, but this is usually an illusion. The collision is never perfectly elastic and when $M_{in} \ll M_{out}$ it is highly likely that that the inner liner will experience a significant jump in temperature due to shock effects. The reason for using a solid liner is its stability with respect to short wavelength perturbations. Heating of the inner liner will tend to soften it. If the liner actually melts, then the short wavelengths (which have large growth rates) will no longer be stabilized and could grow to large levels. To examine these issues more quantitatively, we have performed detailed two-dimensional simulations of colliding shells.

III. NUMERICAL MODELING

One-dimensional Lagrangian calculations were performed to obtain the kinematic dynamics of colliding liners. The calculation employed a sinusoid-like current pulse obtained from actual PEGASUS experiments. A typical current pulse current pulse has a peak current of

6.5 MA with a rise time of 7.1 μs. These are not peak parameters for the PEGASUS capacitor bank, but are appropriate for implosion of so-called Standard Pegasus liners[14]. Such liners are fabricated from Al-1100 alloy, with an outer radius of roughly 24 mm and an inner radius of 23.5 mm. For these calculations, the outer radius of the outer liner was 24.04 mm and its thickness was 0.54 mm. The inner liner thickness was 0.40 mm and its outer radius was 12.4 mm. An additional 1.0 mm of "foam" was added on the outer surface of the inner liner to mitigate shock heating.
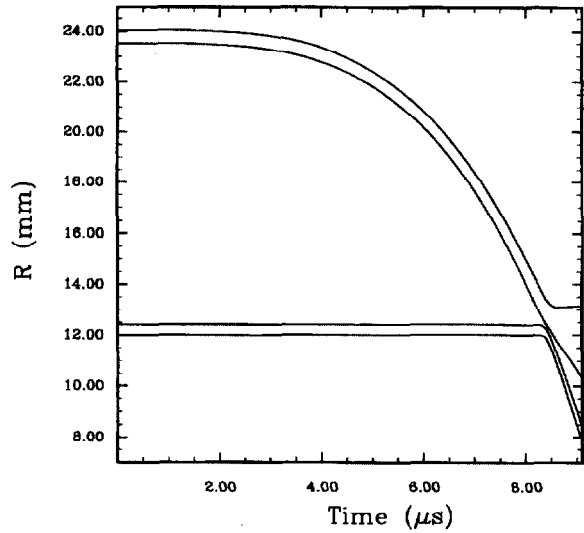

Figure 1. Motion of liner surfaces being driven by a PEGASUS current drive; $I_0 = 6.5$ MA, $\tau = 7.1$ μs.

Fig. 1 shows that the inner liner has been accelerated in a non-destructive manner.

Analysis of the surface motion indicates that the inner surface attained a velocity of almost 6.3 km/s after the collision, while the outer surface reached 5.8-5.9 km/s. For the initial dimensions of this configuration, the point mass collision, Eqs. (3), gives a final velocity of over 6.5 km/s.

The velocity discrepancy is a measure of the inelasticity of the impact. Fig. 2 shows the temperature of the outer surface of the inner liner as a function of time. For the Al-1100 alloy, which is quite close to pure aluminum, ambient condition melting occurs at 0.88 eV. The figure indicates that the inner liner surface briefly exceeds the melting temperature, but then rapidly drops below that level. Examination of numerical zones further inside the liner show even less heating.
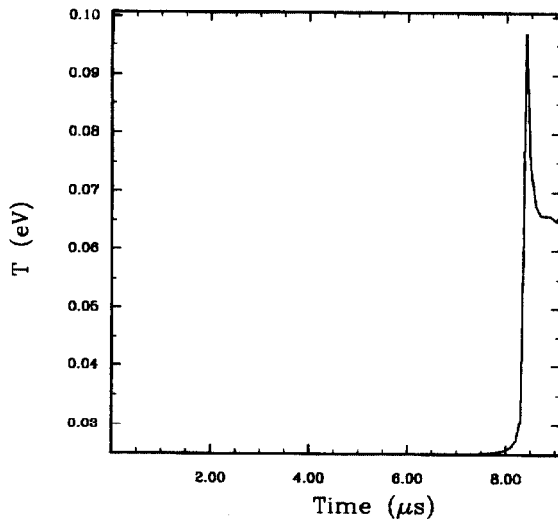
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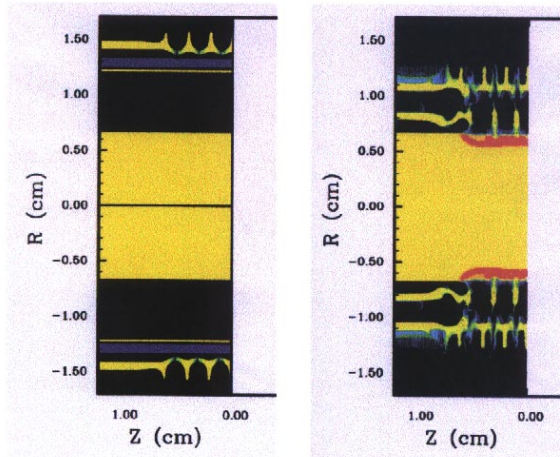Figure 2. Temperature of outer surface of inner liner as a function of time

Figure 3. (a) Density distribution of liners just before impact (t=7.8 μs); (b) Density distribution after impact (t=8.9 μs).

Two-dimensional Eulerian MHD calculations were performed to examine the effect of the collision on a Rayleigh-Taylor unstable liner. The configuration had the same radial dimensions as the one-dimensional Lagrangian calculations. In addition, an initial perturbation of 16 μm amplitude (peak-to-peak) was imposed on the surface of the outer liner. The wavelength was 2 mm. Three wavelengths of perturbation and 6 m of smooth liner were modeled. Fig. 3(a) shows the density distribution slightly before impact (t = 7.8 μs).

The unstable half of the liner has grown to such a large amplitude (roughly 1600 μm) that it is about to rupture the liner. The initially smooth half is not effected by this growth. Fig. 3b at a time of 8.9 μs shows relatively little growth on the smooth side, while the imprinting which

occurs on the other liner half has completely ruptured the inner liner before it has reached the target at a radius of 7 mm.

In analyzing the calculation shown in Figures 3(a) and 3(b), it is evident that the process of colliding liners does not provide much perturbation improvement when the external perturbation is already strongly established. It actually does improve the performance slightly, since the outside liner would have completely ruptured by a radius of 13 mm. The inner liner is still intact at a radius of 11 mm. By a radius of 10 mm, however, it is no longer intact. Additional computational studies have shown that the performance of the inner liner can be improved if the external perturbation is not so large. We are still quantifying these results

IV. COMPARISON OF PRELIMINARY DATA TO CALCULATIONS; CONCLUSIONS

An experiment was fielded recently that was similar to the two-dimensional calculation discussed in the previous section. (The similarity of that experiment to the calculation was the reason it was discussed, in fact.) The data from that experiment is still being analyzed by the joint LANL/VNIIEF team that fielded it. We will therefore defer details. Two salient features emerged from the radiographs immediately. First, the inner surface of the inner liner was in close agreement to the calculations shown in Fig. 3(b), and also to the analogous VNIIEF calculations. Second, there was no evidence of well-defined separation between the two liners after the impact. Fig. 3(b) clearly shows such a separation. As a preliminary conclusion, we find that while we are able to model certain aspects of colliding liners very satisfactorily (i.e., the inner surface), other important properties of the collision process will require a significant improvement in our modeling capabilities. We are optimistic about the colliding liner process, especially for accelerating non-conducting liners or liners with higher resistivity than aluminum. It is not clear how much effect the process has in ameliorating the effects of Rayleigh-Taylor instability.

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